Appendix I. Metrics and Diagnostics for Characterizing Thermal Distribution Systems In Commercial Buildings

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PIER Contract Number: 500-98-026

December 6, 2002

Proposed Metrics and Diagnostics for Characterizing The Performance of Commercial Thermal Distribution Systems

I.1 Overview

In practice, thermal distribution systems often do not perform as well as intended by the design process, partially because conventional building design processes do not adequately address distribution system performance, and partially because thermal distribution systems are generally not installed or operated according to design.

One common link between these two problems is the need for a set of metrics (or yardsticks) by which the performance of these systems can be characterized. Such metrics are needed both to simplify the inherent complexities associated with the design process, and to digest diagnostic measurements or monitoring results into a manageable number of descriptors. The idea behind metrics is to distill down the complexities of different systems to a single descriptor, or limited set of descriptors, that allows those systems to be compared with each other on a level playing field. One concrete example of a set of metrics is the way that automobiles are characterized and compared, using parameters such as wheelbase (size), horsepower (capacity), and miles-per-gallon (performance, or fuel-efficiency).

ASHRAE Standard 152P already provides energy performance metrics for residential thermal distribution systems. This Standard could serve a similar function for small commercial buildings that use small packaged HVAC systems similar to residential equipment. However, it does not address non-energy performance issues, nor can it be used to address energy efficiency issues in large commercial buildings.

In approaching the issue of metrics for thermal distribution systems in commercial buildings, a key distinction needs to be made between large and small commercial buildings. That distinction stems from two key differences between these two types of buildings, which are the:

1. fraction of HVAC energy used by the fans and pumps, and
2. complexity and variability of the systems.

For example, in large buildings, 35 to 50% of HVAC energy use occurs in the fans and pumps, versus approximately 15% in small commercial building systems. The larger fraction of fan and pump energy used by large buildings is largely due to longer distances, higher pressures, and continuous fan operation in the larger buildings.

The goal of this document is to provide a starting point for developing a set of metrics that describe thermal distribution system performance in both small (thermally dominated) and large (fan-power dominated) commercial buildings. This set of metrics needs to include energy (consumption and demand) metrics, as well as environmental indices (e.g., health, comfort, and safety). Because the two types of buildings operate very differently and tend to serve different purposes, we have assembled two distinct sets of metrics, with some overlap between the two sets. In addition, to keep the document scope manageable, most of the metrics and sub-metrics presented here apply only to air distribution systems.

I.2 Full-Sector Commercial Distribution Metrics

I.2.1 Energy Efficiency

At the most global level, the key energy metric for all types of thermal distribution systems is the *overall energy efficiency*, which is defined as:

Sum of the absolute values of all the space loads in the building Divided by the Sum of the absolute values of all heating and cooling energy delivered at heat exchangers for space conditioning plus all fan and pump energy consumption

This metric accounts for both thermal and transport efficiencies, accounts for simultaneous heating and cooling inefficiencies, includes energy added by terminal reheat, and can be used to compare distribution systems that use different transport media (e.g., air versus water). On the other hand, although it is conceptually useful, it is very difficult to calculate this metric for anything but a building on paper or in a computer. In a field situation, measuring the parameters required to calculate this metric generally is not practical.

There are a number of sub-metrics that contribute to the global energy efficiency. One that applies to both air and water systems is the *overall thermal efficiency*, which is the ratio of heating or cooling energy delivered at the supply grilles or radiators to the heating or cooling energy that heat exchangers deliver to the distribution system for space conditioning.

If we limit ourselves to air-only systems, there are a number of other sub-metrics that should apply to all commercial building thermal distribution systems, including:

1. The supply duct fractional air-leakage [%],
2. The normalized fan power [W/cfm, W/ft^2], and
3. The normalized airflow [cfm/ft^2].

I.2.2 Indoor Environmental Performance

It is important to recognize that distribution systems interact in a myriad of complex ways with other components of the building. This is true both with respect to comfort, and with respect to Indoor Air Quality (IAQ). Without even considering the entire building, it is clear that in most cases, the conditioned zones themselves are part of the distribution system, which alone adds enormous complexity. As an example, for an air system, the conditioned space can be seen as the part of the distribution system that connects the supply grilles to the return grilles. The thermal comfort within the space and the energy efficiency would be impacted by paths taken between those grilles, which in turn depend on the location and operating characteristics of the grilles, as well as on the air temperatures and flows through the grilles. Some concrete examples include the impacts of cold air distribution grilles on "dumping" cold air within the room, or the impacts of VAV induction airflows on the degree of mixing within the room. If we wanted to truly compare all types of distribution systems, we would have to address the issue of radiant versus air temperature, which is different for convective versus radiant delivery, and the location of the grilles or radiators relative to the windows. If we wanted to address the problem at this level, we would also need to address the impacts of localized distribution systems, such as user-controlled grilles at workstations. The time requirements needed to determine parameters associated with these complex metrics place practical limits on the scope of the indoor environmental (and even energy efficiency) metrics that should be considered. Based upon these arguments, we have attempted to limit the scope of our comfort and IAQ metrics to issues that can be isolated to the distribution system itself, and that do not involve more complex interactions with other environmental factors.

With respect to thermal comfort, we chose to limit the metrics to quantifying heating or cooling energy delivery at the distribution system entries to each conditioned space, and to ignore any further distribution issues within the spaces (e.g., to ignore how the air travels “down the road” after leaving supply grilles). Our global metric for thermal performance is the thermal uniformity between the spaces being conditioned; more specifically, the *zone-by-zone variance of the room temperatures*. This parameter applies to all systems, and includes the impacts from the weather and building operating conditions. This metric has the opposite problem as compared to the overall energy efficiency – it is more straightforward to determine in the field as compared to predicting the value from building plans or computer simulations.

With respect to IAQ, a thermal distribution system can impact it in a number of different ways, including the distribution system’s impacts on:

1. The entry of pollutants,
2. The creation/incubation of pollutants, and
3. The transportation and dilution of pollutants.

Another environmental performance metric that can apply to all types of systems is the *noise* level, which is similar to thermal uniformity in that it is easier to measure in an actual building than to predict. This metric can be defined as the temporal average increase in noise level when the distribution is in normal operation, compared to when the system is not operating.

Because of the limited scope here, some of the metrics that we examined but chose not to utilize include: the Air Diffuser Performance Index (ADPI), which characterizes mixing external to a diffuser, and the set of comfort indices outlined in ASHRAE Standard 55, which are widely used in assessing comfort.

I.3 Small Commercial Air Distribution System Metrics

This section presents a proposed set of metrics to characterize the performance of thermal distribution systems in *small* commercial buildings (thermally dominated systems). This set of metrics should apply to most rooftop packaged units, as long as they do not have zoning or variable air volume controls.

I.3.1 Energy Performance

The key metrics for the energy performance of small commercial buildings come directly from ASHRAE Standard 152P. The measurement and calculation procedures in that proposed standard yield two efficiency metrics:

1. *Seasonal* distribution system efficiency for energy consumption calculations, and
2. *Design* efficiency for equipment sizing/selection and peak-demand calculations.

To determine these efficiencies, the draft ASHRAE standard contains procedures for obtaining a number of sub-metrics, including:

1. The supply and return duct fractional air-leakage,
2. The effective leakage area (ELA),
3. The duct operating pressures, and
4. The distribution effectiveness for thermal losses resulting from heat conduction through duct walls (the fraction of the sensible capacity lost due to conduction through the duct walls).

The key issues associated with using this standard for characterizing small commercial building energy performance are that the standard:

1. Does not address *continuous fan operation* and its impact on energy performance, and
2. Does not address *fan power* in any way.

Adding a simple methodology for calculating the impacts of fan energy use and the thermal efficiency impacts of continuous fan operation can augment the metrics in this standard. To accomplish this, a sub-metric that is required in addition to those in the ASHRAE Standard is the fraction of hours in a year that the fan is running without the air-conditioner or furnace operating. This parameter needs to be calculated separately for the heating season and the cooling season. The seasonal values can then be used to calculate the energy losses while the fan is off, which can then be combined with the equipment-on efficiencies on a fractional time basis. Incorporating this effect means that equipment capacity becomes an important characteristic. A more complete treatment would be needed if variable capacity equipment or a variable speed fan were accommodated.

I.3.2 Indoor Environmental Performance

As noted in Section I.2.2, the environmental-performance metrics described in this appendix are limited in scope. In the case of small commercial buildings, Indoor Environmental Performance can be characterized by six metrics and sub-metrics: four for thermal comfort, and two for IAQ/Safety.

For small commercial buildings, the two thermal comfort metrics are:

1. The ratio of delivered thermal capacity at the supply grilles to the thermal capacity delivered by the HVAC equipment into the distribution system, and
2. The standard deviation of the temperatures in the different spaces being conditioned by the system.

The ratio of delivered capacity to equipment capacity is a comfort measure in that it quantifies the impact of the distribution system on the HVAC system's capability to maintain comfort under design conditions. This metric can be calculated in the same manner as the duct-system energy efficiency under design conditions in ASHRAE Standard 152P.

The standard deviation of the temperatures in the different zones is a measure of how well the distribution system is distributing heating and cooling to the zones that need it. Because of the difficulty associated with quantifying the standard deviation of zone temperatures in the field or from building plans, we suggest that two sub-metrics be used:

1. The standard deviation of the *temperatures delivered at the supply grilles*, and
2. The standard deviation of the *ratio of delivered supply grille airflows to design supply grille airflows*.

The first of these sub-metrics is simply based upon the assumption that there are likely no purposeful means within the design of the system to alter the delivered temperatures on a zone-by-zone basis (e.g., reheat coils), assuming the definition of the types of systems/buildings covered by this section is appropriate. In other words, all rooms should be receiving the same temperature air.

On the other hand, floor-area normalized airflows vary in the design process between rooms, and therefore measured airflows should be compared to design airflows rather than to each other. The problem is that most buildings of this type do not receive zone-by-zone load calculations, or those calculations are impossible to obtain. In cases where no design information is available, the normalized airflow comparison has to be made relative to a nominal airflow per unit floor area (or the building average airflow per unit floor area).

The impact of the distribution system on IAQ in a small commercial building can be quantified in a limited manner based upon the following two sub-metrics:

1. The distribution system impact on conditioned-space and buffer-zone *pressures*, and
2. The distribution system impact on overall *air exchange rates*.

These metrics only address impacts of the distribution system on entry of pollutants and dilution of pollutants. The creation/incubation of pollutants is not addressed at all, and the other two impacts are not treated in an exhaustive manner.

The first sub-metric (*pressure* impacts) can be quantified in terms of two numbers:

1. The maximum *depressurization* of any building zone relative to the outdoors under any normal operating condition, and
2. The maximum *pressurization* of any building zone relative to the outdoors or other building zone under any normal operating condition.

The two values are separated because of their different implications, and because many commercial buildings are purposefully operated at pressures somewhat higher than outdoors.

Depressurization is generally the pressure imbalance that has the most negative impacts, including drawing in hot unconditioned outdoor air (and ozone) through the building shell in the summer, causing exterior doors to be difficult to open, and causing potential combustion-product backdrafting and spillage problems. Backdrafting and spillage are important IAQ concerns, as they cause combustion gases (pollutants) to be brought into occupied spaces. In addition, negative pressures in building spaces often cause pollutants to be carried from one zone to another (e.g., shop areas to office areas).

On the other hand, pressurization can cause doors to blow open, and forces hot humid air through the building shell in the winter, potentially causing moisture damage. In addition, if a zone that contains pollutants is pressurized relative to surrounding zones, the surrounding zones may become contaminated.

The second IAQ sub-metric that can be used for thermal distribution systems in small commercial buildings is their impact on overall *building air exchange rate*. This is the simplest means for describing the impact of these systems on pollutant dilution, as it addresses only their average pollutant dilution impact, or average outdoor-pollutant entry impact. Even this simple metric is complicated by the fact that most commercial buildings use an intentional outdoor air intake coupled to the return air to provide ventilation, and by the fact that unbalanced distribution system airflows do not add linearly to natural ventilation rates. As such, this metric also consists of two numbers, both normalized by conditioned-space volume:

1. The *balanced* leakage airflows through the supply and return ducts (i.e., the amount of leakage airflow out of the supply ducts that could be offset by the amount of leakage airflow into return ducts, or vice versa), and
2. The *unbalanced* leakage airflows through the supply and return ducts (i.e., the leakage airflow differential between the supply and return ducts).

I.4 Large Commercial Air Distribution System Metrics

This section presents a proposed set of metrics to characterize the performance of thermal distribution systems in *large* commercial buildings (fan-dominated systems). This set of metrics should be applied to packaged and built-up systems, whether or not they have Constant Air Volume (CAV) or Variable Air Volume (VAV). The key differences between the metrics for large and small commercial buildings are that the ones for large commercial buildings focus on transport energy use, and a more detailed treatment of zonal performance.

I.4.1 Energy Performance

The working assumption for large commercial buildings is that the distribution systems are generally located within the conditioned space. The only exceptions to this assumption are when the ducts are located outdoors, or when the ducts are located in a top-story plenum that is insulated at the ceiling or vented at the roof deck. If a duct system (or a portion of a duct system) meets either of these conditions, its energy efficiency can be calculated with the same ASHRAE 152P methodology used for small commercial buildings, except that the fan power efficiency should be calculated as outlined in this section.

For large commercial buildings, the primary metric for distribution system performance is the transport energy (e.g., total energy used to transport air) per unit thermal energy delivered ($kW_{transport}$ / $kW_{thermal\text{-}delivery}$). This metric obviously depends on the distance over which thermal energy needs to be transported, and therefore is a function of the size and geometry of the building. On the other hand, by using this as the primary metric, the use of distributed heating and cooling equipment can be compared with central systems. This metric also allows for comparisons of VAV and CAV systems, as well as the impacts of thermal/leakage losses on fan power. Calculating this parameter for a building on paper or using a computer is relatively straightforward, excluding any impacts of improper installation or operation. Determining this parameter in a building that has already been built is somewhat more difficult because measuring the total heating or cooling energy delivered to each zone requires air temperature and flow sensors at every grille and temporally continuous measurements.

It should be noted that this definition implicitly assumes that thermal energy, including heat generated by transport, is only transferred to the conditioned zones through the supply grilles (or radiators for a hydronic system). This assumption would be violated by exposed ductwork within the conditioned space. Similarly, this parameter does not properly account for reductions or increases in cooling or heating loads created by heat exchange with buffer spaces. These two limitations are not a problem for a building in the design process, as the thermal delivery to the zones is by definition the load in those zones. On the other hand, measurements of this parameter in a real building would need to be corrected for these two effects.

There are several common sub-metrics that can be used to characterize fan power in large commercial buildings, including the following three:

1. The specific fan power [W_{fan}/cfm],
2. Fan airflow density [cfm/ft^2], and
3. Normalized fan power [W_{fan}/ft^2].

The limitations and precise definitions of these parameters merit further discussion.

The airflow (cfm) used for *specific fan power* [W_{fan}/cfm] can be defined in terms of the airflow delivered by the fan, or in terms of the airflow delivered to the conditioned spaces. Using the first definition is simply a measure of the efficiency of the fan airflow, which is determined by the airflow resistance of the duct system (leaks in the duct system serve to reduce its resistance). The existence of duct leaks therefore would produce a bias that reduces the value of the specific fan power. The second definition (using the airflow delivered to the zones) incorporates impacts of duct leakage, because leak reduction is excluded in the delivered airflows, thereby increasing the specific fan power. We suggest using the second definition. However, it needs to be made clear that neither definition specifically accounts for the impacts of thermal losses from the ducts (these losses increase the amount of air that needs to be moved, which affects the specific fan power by changing the operating point of the fan).

The *fan airflow density* [cfm/ft^2] is another fairly common metric for describing HVAC systems, however it also needs some clarification. As with specific fan power, the airflow at the fan is not necessarily equal to the sum of the grille airflows. If we use fan airflow in our definition, it implicitly penalizes duct leakage, in that more air needs to be moved to satisfy the load. In contrast, using the airflow at the grilles ignores the impact of duct leakage. To avoid double-counting the impacts of leakage, we define fan airflow density in terms of airflow at the grilles. Unlike specific fan power, both the airflow at the fan and the airflow at the grilles are affected by thermal conduction losses through the duct walls, because thermal losses translate into the need to move more air at both places. By defining this parameter based upon airflow at the grilles, we have a parameter that is not impacted in any significant way by duct leakage, but that does reflect thermal conduction losses.

The *normalized fan power* [W_{fan}/ft^2] is the most comprehensive and general of these common sub-metrics, because it includes the impact of both leakage and conduction losses, and could apply equally well to air or hydronic distribution systems.

An important point that has generally been ignored in conventional analyses of the energy impacts of duct leakage and conduction losses is their impact on fan power in large commercial buildings. In particular, the issue is that thermal or leakage losses reduce the quantity of energy that is delivered to the zones being conditioned. Thus, to meet the loads in these zones, more energy needs to be transported by the fan to make up for the energy that is lost along the way. As more energy transport is usually accomplished by moving more air, this also translates into larger pressure drops through the ductwork. Thus, as fan power scales with the product of the airflow and the pressure differential, fan power increases dramatically as a result of thermal or leakage losses from the supply ducts[1]. Note that this is true even when the losses are all within the envelope of the building.

One way to conceptualize the fan power impacts of duct losses is to think of leakage and conduction losses as short-circuiting the fan. If the supply ducts are in a ceiling-plenum return, then some of the losses from the supply ducts to that plenum are returned to the supply fan via the return air. Some of these losses are also delivered to the conditioned spaces through conduction across the ceiling tiles, although this is not always beneficial when there are simultaneous heating and cooling loads in different spaces.

The losses from the ducts can be thought of as being partitioned by a "current-splitter", with the larger fraction of the losses going down the path of least resistance. The two competing paths are back to the fan via airflow through the return plenum, and to the conditioned spaces via conduction through the ceiling plenum tiles. The effective conductance of the return air path is its airflow times the specific heat of the air, while the effective conductance of the ceiling tiles is their area divided by the R-value of the tiles. In general, the ratios of these two conductances imply that most of the energy is sent back to the fan.

The sub-metric that can be used to quantify this effect of duct losses on fan power is called the *duct-loss power ratio*, defined as the ratio of the fan power for an airtight, perfectly insulated duct system, to the fan power for the duct system in question. This factor depends upon the leakage and conduction losses from the duct system, and on the ratio of the effective conductance of energy back to the central system to the effective conductance of energy into conditioned spaces. It should be noted that this parameter does not account for the fact that conduction to conditioned spaces is not always beneficial.

One important factor that has to be addressed when calculating the duct-loss power ratio is the impact of VAV boxes, in particular the impact of plenum air induction at these boxes. The issue is that the induction boxes represent a third path for the energy losses from supply ducts to leave the ceiling plenum. They draw in air that was otherwise going to be drawn back to the central fan; they then blow that air into the conditioned zones. In this respect, the induction airflows represent another conductive path between the return plenum and the conditioned spaces. Thus, when calculating the duct-loss power ratio, the product of the induction airflows (less any induction air leakage back into the plenum downstream of the induction fan) and the specific heat of air needs to be added to the conductance of the ceiling tiles.[2]

Some additional sub-metrics that can be used for characterizing energy performance in large commercial buildings are similar to those for small commercial buildings:

1. The supply and return duct fractional leakage,
2. The effective duct leakage area (ELA),

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[1] For example, if we assume that the airflow resistance of a typical duct system results in the pressure differential across the supply fan being roughly proportional to the airflow squared, then a 10% increase in supply airflow causes a 33% increase in supply fan power; a 20% airflow increase causes a 73% power increase. Note that this is an overly simplistic way to assess airflow impacts on fan power, but serves as a rough first order approximation.

[2] To complicate the issue, some of the induction air can leak back into the ceiling plenum downstream of the induction fan if the supply ducts transporting the induction air to the conditioned spaces are leaky.

3. The duct operating pressures, and
4. The distribution effectiveness for thermal losses resulting from heat conduction through duct walls (the fraction of the sensible capacity lost due to conduction through the duct walls).

The difference in large commercial buildings is that these parameters need to be calculated for sections of the ductwork, and not simply for the entire system. For example, the duct leakage needs to be split between before the VAV boxes and after the VAV boxes, as does the distribution effectiveness and the operating pressures.

Most small commercial buildings and CAV systems in large buildings have single operating points, whereas VAV systems have a spectrum of operating points. The operating point impacts the operating pressures and the distribution effectiveness. These parameters should be calculated/measured for VAV systems at design conditions, as well as at a part-load point that is somehow related to the seasonal average value. The seasonal operating condition is not so difficult to quantify for a building on paper, but is likely to be problematic in measurement situations. Determining this condition in a building requires measurements over a reasonable time period to look for trends. For VAV boxes with heating coils, the energy gain/loss induced by the heating coils needs to be included in all distribution effectiveness calculations.

I.4.2 Indoor Environmental Performance

There are several metrics currently in use to describe comfort performance in large commercial buildings, some of which are even focused on the distribution system. One in particular is related to the distribution from the heating/cooling equipment to the supply grilles, rather than distribution within the zones after the airflow leaves the grilles. This metric specifically excludes the metrics that treat room air mixing or temperature mixing, or that try to address zone velocity, humidity, or radiation impacts on comfort. Although our definition of the distribution system ends at the entry points to the zone, the spatial temperature variation of supply grille air temperatures is still a useful surrogate metric for the capability of the distribution system to affect comfort. For each zone, this variation can be represented by the standard deviation of the temporally coincident air temperatures at each supply grille serving that zone. From zone to zone, the spatial temperature variation of supply grille air temperatures can be represented by the standard deviation of the temporally coincident zonal average supply grille air temperatures.

The key difference between the IAQ metrics used in large commercial buildings and those described for smaller buildings is that large commercial buildings usually cannot be treated as single zones; they have different zones with different load requirements, and the dilution of pollutants is affected by local air change rates (e.g., in a room) and transfer air change rates between zones, as opposed to the overall air change rate of the building. In a manner similar to using the standard deviation of normalized supply grille airflow for small systems, one can adopt basic statistics (i.e., max, min, mean, and standard deviation) of supply airflow to characterize the mechanical ventilation impact for large systems under certain operating conditions. In this case, supply airflow means the sum of all supply grille airflows within the same zone, normalized by occupancy or zone floor area. The other key issue with large commercial building metrics is the need to define typical operating conditions for systems that are often very complex (e.g., temporal variation in VAV systems, additional airflow through induction units).

In assessing the performance of an air distribution system and its impacts on comfort and air quality, it is almost impossible to obtain quantitative measurements, but it is relatively easy to obtain qualitative information about a system's design, operation, maintenance, and control. Consequently, a checklist is needed. Some of the characteristics to record include:

- Weather Conditions (temperature, wind speed, humidity)
- Faulty or closed outdoor air dampers
- Failed/damaged ventilation or exhaust fans
- Dirty ducts and/or filters
- VAV terminal box dampers that close off completely
- Failed fire dampers that might close off airflow
- Lack of a purge cycle at system startup
- Faulty fan-tracking control on air handling system
- Faulty building pressure set point (e.g., negative building pressure)

I.5 Diagnostics for Evaluating Thermal Distribution System Metrics

I.5.1 One-Time and Short-Term Diagnostic Measurements for Energy Performance

I.5.1.1 **Duct Leakage:** Duct leakage characterization includes determining the supply duct air-leakage ratio, which can be performed using two independent methods:

1. Subtracting the sum of supply grille airflows from the measured supply fan airflow, and
2. Calculating leakage airflow from measured duct effective leakage area (ELA) and duct operating pressures. The difference between characterizing large and small systems is that we separate the evaluation of operating pressure and ELA based on main-duct and branch-duct levels, respectively

For CAV systems, the diagnostics involve a one-time measurement under fixed operating conditions. For large VAV systems, the characterization of air-leakage ratio is limited to one particular operation condition that is likely to be fixed during airflow measurements. However, for the second diagnostic, the operating pressures and supply airflows need to be monitored continuously over a range of normal operating conditions (e.g., days, and perhaps seasonally depending on how induction fans operate).

I.5.1.2 **Distribution Effectiveness:** Distribution effectiveness (*temperature effectiveness*), which quantifies thermal conduction losses, can be determined by measuring the temperature drop/rise along supply ducts (e.g., between air-handler coils and VAV box inlets, and between VAV boxes and supply grilles). For CAV systems, temperatures and airflows can be measured under steady-state operation, with and without reheat operation. For VAV systems, temperatures and airflows need to be measured over a range of normal operating conditions to account for variable airflow, reheat coil operation, and induction airflows.

I.5.1.3 **Duct-Loss Power Ratio:** Diagnostics for this metric require further development before they can be practically applied.

I.5.1.4 **Equipment Performance:** Some relevant characteristics in small commercial buildings are the capacities of the cooling and heating equipment and the fan, including total fan airflow (cfm). In addition to measuring airflows through the equipment, determining the cooling and heating capacities requires measurements of temperature and humidity upstream and downstream of the equipment, so that enthalpy changes can be calculated.

I.5.1.5 **Fan Operation:** This metric is used for small CAV systems. One can determine the fan's on-time by recording when the space conditioning unit is on and off and then calculate the ratios of fan operation hours when the unit is off to total fan operation hours during the cooling and heating seasons, respectively. Although short-term data are useful, data from a whole-year of monitoring can provide additional important information on energy saving implications due to seasonal effects.

I.5.1.6 **Cycle-Average Distribution Efficiency:** This metric is used for small CAV systems. It can be determined on a minute-by-minute basis throughout compressor and furnace cycles by short term monitoring of air temperatures and flows.

I.5.1.7 **Transport Energy Ratio ($kW_{transport}/kW_{thermal\text{-}delivery}$):** This metric is the total energy used to transport air ($kW_{transport}$) per unit thermal energy delivered ($kW_{thermal\text{-}delivery}$), and is only used for distribution-system performance in large commercial buildings. Determining this parameter in a building that has already been built tends to be impractical because measuring the total heating or cooling energy delivered to each zone requires air temperature and flow sensors at every grille and temporally continuous measurements.

I.5.1.8 **Specific Fan Power (W_{fan}/cfm):** This metric does not account for the thermal losses along the ductwork. One of the required measurements is the fan power, either measured one-time (CAV) or through short-term monitoring (VAV). The cfm is the total delivered airflow, which is obtained by measuring the supply grille airflows under a typical operating condition (heating, cooling, or mechanical ventilation mode). This parameter is relatively constant for CAV systems, changing only as ductwork gets dirty or begins to leak, or as fans wear out or become dirty. For VAV systems, this parameter changes as the system operating point changes. In addition, for VAV systems with induction units, it is practically impossible to separate the airflow delivered by different components. In general, determining this metric is impractical for VAV systems with or without induction units, unless for diagnostic purposes the system is placed in a fixed operating mode and the induction fans are turned off.

I.5.1.9 **Fan-Airflow Density (cfm/ft^2):** The airflow per unit floor area in each zone can be determined by measuring the conditioned floor area and the total airflow delivered to each zone under certain operating conditions. As described in Section I.4.1, this metric reflects the impacts of thermal conduction losses while not discounting duct leaks in a significant way. Like specific fan power, the metric is impractical for VAV systems, unless for diagnostic purposes the system is placed in a fixed operating mode and the induction fans are turned off.

I.5.1.10 **Normalized Fan Energy (W_{fan}/ft^2):** As described in Section I.4.1, this metric reflects the combined impacts of duct leaks and thermal conduction losses, and can be examined for large commercial systems, especially CAV systems, by measuring fan power and the conditioned floor area. A one-time measurement of power is needed for a CAV system, whereas short-term monitoring over a range of normal operating conditions is needed for a VAV system.

I.5.2 One-Time and Short-Term Diagnostic Measurements for Environmental Quality Performance

I.5.2.1 **Duct Loss Location:** Inspecting ducts involves qualitative (e.g., visual) and quantitative measurements. This includes inspecting the ceiling plenum to determine the location of insulation and venting, and conducting pressure and temperature measurements to determine the location of the air and thermal boundaries. In addition, for large systems located in multi-story buildings, it is necessary to examine the ceiling plenum for the top floor in this regard. These diagnostics can be conducted on a one-time basis.

I.5.2.2 **Duct-System Airflow Resistance:** Determining airflow resistance involves measuring airflows and operating pressures in supply and return ducts, including at a minimum the pressures in the equipment plenums and at the supply grilles. For CAV systems, this can be a one-time measurement in a desired mode (e.g., heating, cooling, and/or mechanical ventilation). For VAV systems, continuous monitoring is required over a range of normal operating conditions (e.g., several days).

I.5.2.3 **Balanced and Unbalanced Leaking Airflow:** This applies to small systems only. It involves measuring the leakage airflows for the supply and return ducts.

I.5.2.4 **Zonal Pressure Distribution:** The zonal pressure distribution can be measured to the nearest 0.1 Pascal under different operating conditions, and can include measurements of both occupied and buffer zones, with reference to outdoor air or to an adjacent zone. Zone pressurization and depressurization data when coupled with zonal leakage area measurements can provide useful information about the potential for unintended airflows that might affect comfort and air quality.

I.5.2.5 **Comfort Capability Index:** As described in Section I.3.2, this metric is the ratio of delivered thermal capacity at the grilles to the thermal capacity delivered by the HVAC equipment. It can be determined in the same manner as the duct-system energy efficiency under design conditions in ASHRAE Standard 152P.

I.5.2.6 **Spatial Temperature Variation:** The spatial distribution of air temperatures can be determined by measuring the temperature of air exiting each supply grille. This metric includes a combination of standard statistical parameters (i.e., maximum, minimum, mean, and standard deviation), which can be calculated using the measured temperature data. For small systems, the statistical parameters are based on all the supply grilles; for large systems, the metrics should be presented at two levels: one within each zone; the other between zones based on the mean air temperature at all supply grilles for a zone. Note that measuring the supply air temperature at every grille in a large commercial building is impractical (particularly for a building with a VAV system); in this case, sampling techniques need to be used to obtain representative information.

I.5.2.7 **Spatial Airflow Variation:** The spatial distribution of supply airflow can be determined by measuring airflows at all supply grilles normalized by the served floor area (cfm/ft^2) or occupancy (cfm/person), and compared to the associated design supply airflows (cfm/ft^2, or cfm/person). The relevant metric for a single zone is the standard deviation of the ratios of actual airflows to the design airflows. For CAV systems, this involves a one-time measurement. In general, determining this metric is impractical for VAV systems with or without induction units, unless for diagnostic purposes the system is placed in a fixed operating mode and the induction fans are turned off.

I.5.2.8 **Other Qualitative Measurements to Be Recorded:** See the **c**hecklist described in Section I.4.2.